# Nonlinear Internal Waves in the South China Sea

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## LONG-TERM GOAL

To study nonlinear ocean internal wave processes in the South China Sea by using satellite synthetic aperture radar (SAR) imagery, in-situ data, and numerical models to understand the environmental effects (e.g. bottom topography, shoaling, mixing, and current/shear) on nonlinear internal wave generation, evolution, and dissipation.

## OBJECTIVES

The objective of this study is focused on nonlinear internal wave and mesoscale feature (e. g. eddies, fronts) observations in the shelf-break region of the SCS. The effort is to support the Asian Seas International Acoustics Experiment (ASIAEX) for the collection and analysis of ERS-2 SAR and RADARSAT ScanSAR data in the South China Sea (SCS) planned for April 2001. Of particular interest is the generation of huge internal waves caused by the branch out of Kuroshio through Luzon Strait and its evolution on the shelf break into mode-two solitons.

## APPROACH

A field test has been planned by ASIAEX and this joint experiment from US, Russia, Japan, Korea, Singapore, Taiwan and China will be conducted in year 2001. ASIAEX consists two components: one in the South China Sea (centered approximately at 20N, 118E) and one in the East China Sea (centered approximately at 29N, 126E). More than six research ships (one from US, two from China, two from Taiwan, and one from Japan) with scientists from all these countries will participate in this major experiment in 2001. In April 2000, the preliminary survey experiment has been conducted which is providing the geologic and oceanographic data needed for the major field experiment in year 2001. Unfortunately, ASIAEX team did not obtain all the clearances from China needed for the South China Sea preliminary survey in 2000. Therefore, only Taiwan's Ocean Research ships OR-1 and OR-3 conducted the physical oceanography survey in the South China Sea.

The approach is to use the SAR data in conjunction with the in-situ measurements from field experiments to calibrate and validate SAR imaging mechanism of nonlinear internal waves, and to integrate all data by wave model for data assimilation. A validated and calibrated algorithm and model can be very useful for understanding of shelf processes and for the applications of the internal wave effects on acoustic propagation. A parametric study for various environmental conditions to assess the nonlinear effects such as bottom topography (across critical depth), shoaling, stratification, and dissipation has been conducted. The generation and evolution of internal waves (elevation versus depression, and mode-one versus mode-two), and wave-wave interaction will be studied using satellite data in conjunction with in-situ data from the field experiments. All data will be synthesized/integrated by using numerical models.

## WORK COMPLETED

Recently, the internal wave distribution maps have been compiled from more than three hundreds of ERS-1/2, RADARSAT and Space Shuttle SAR images in the East and South China Seas and Yellow Sea from 1993 to 1998 by Hsu et al. (2000) and Hsu and Liu (2000). Based on the internal wave distribution map, most of internal waves in the northeast part of South China Sea are propagating westward. The wave crest can be as long as 200 km with amplitude of 100 m, due to strong current from the Kuroshio branching out into the South China Sea (Liu et al., 1998). From the observations at drilling rigs near DongSha Island by Amoco Production Co. (Bole et al., 1994), the solitons may be generated in a 4 km wide channel between Batan and Sabtang islands in Luzon Strait. The sill between Batan and Sabtang islands is like a saddle point. The proposed generation mechanism is similar to the lee wave formation from a shallow topography in the Sulu Sea (Apel et. al., 1985; Liu et. al, 1985).

In recent South China Sea internal wave study, as a part of the ASIAEX survey program, five moorings have been deployed in April 2000. The moorings consisted of a chain of thermistors and ADCP. Simultaneous SAR coverage from ERS-2 have been collected. The ERS-2 high-resolution SAR images collected from the ground station in National Taiwan Central University were processed in near real-time (two hours). As an example, Figure 1 shows an ERS-2 SAR image of huge internal solitons collected on April 26, 2000 near DongSha Island in the South China Sea. The SAR images were then transferred and interpreted at the Institute of Oceanography, National Taiwan University. Within four hours, the ocean research ship in SCS has received the delineated and mapped SAR image by fax. Based on the satellite information, the Chief Scientist on board can then make a decision to coordinate the survey strategy if needed.

## RESULTS

Internal wave measurements were carried out with ADCP mooring and thermistor chain in April 1999. The location of mooring deployed by OR-1 on April 9, 1999 for 10 days is at northeast of Dong-Sha Island on the shelf break in 425 m water depth. The ADCP data from mooring show mode-one internal solitons from April 15 to 18, induced by the semi-diurnal tides. The maximum current in the mixed layer was about 2 m/s in the west direction, and was more than 1 m/s in the east direction in the bottom layer which is typically induced by mode-one waves.

The most surprised phenomenon is the mode-two solitons observed on April 10, 1999 at 11:00AM. The thermistor chain data from April 10 show the mode-two internal waves with negative temperature fluctuation in the mixed layer and positive value in the bottom layer. The mode-two waves were lagging behind the diurnal tide by about 4-hours since mode-two waves have slower wave speed than mode-one waves. The ADCP data from mooring also confirm the mode-two internal solitons on April 10, 1999 with two-zero crossings in current profile and are consistent with the thermistor chain data.

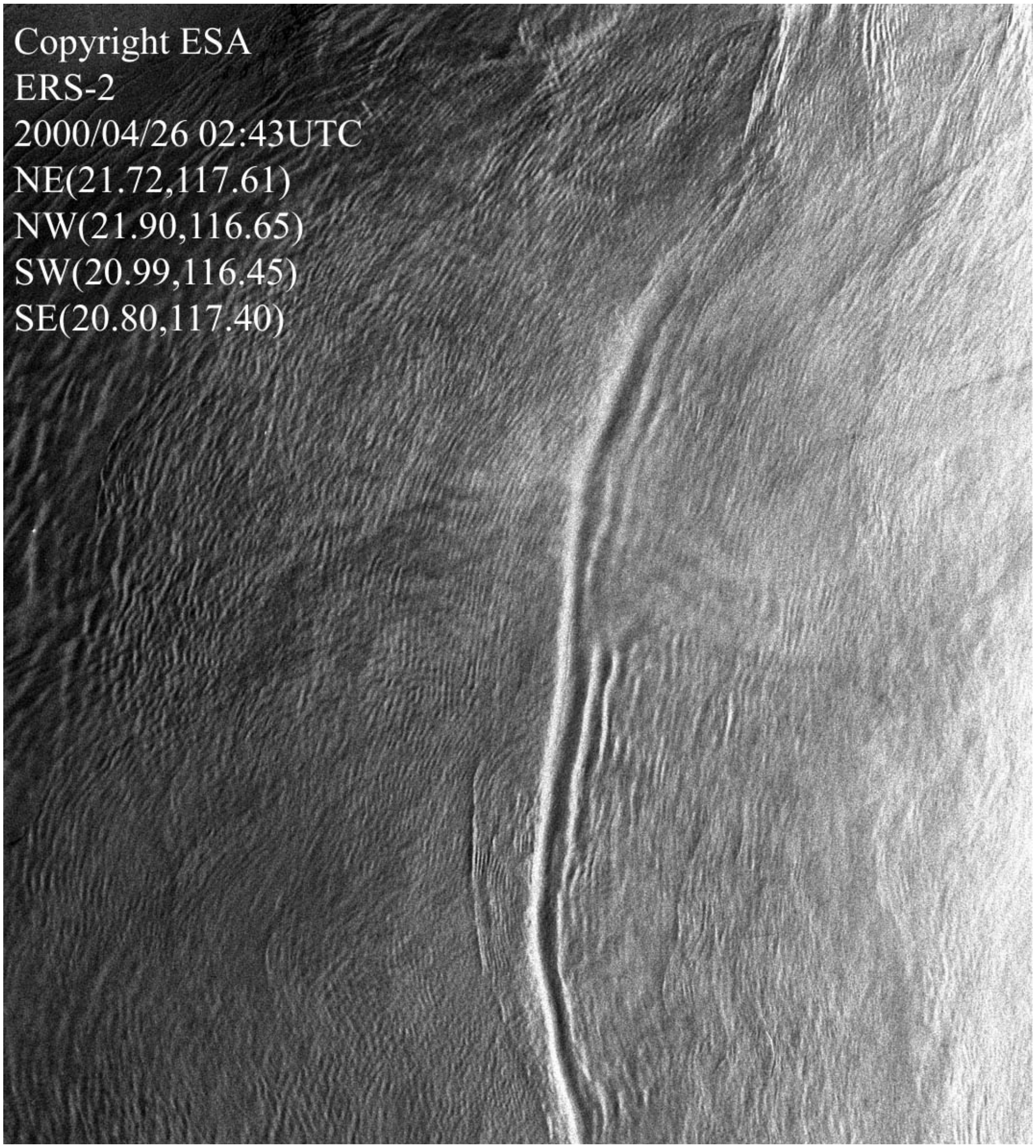


***Figure 1. ERS-2 SAR image of huge internal solitons collected on April 26, 2000 during ASIAEX 2000 near DongSha Island in the South China Sea. (© ESA 2000)***

The mixed layer depth was about 110m (zero-crossing in temperature) from thermistor, and ADCP shows a mixed layer depth of 120m (maximum current). The maximum current induced by these mode-wave was over 1 m/s. The generation of these mode-two waves is most likely due to the intrusion of seasonal thermocline on the shelf.

In recent South China Sea internal wave study, as a part of the ASIAEX survey program, five moorings have been deployed in April 2000. The moorings consisted of a chain of thermistors and ADCP. Simultaneous SAR coverage from ERS-2 have been collected and analyzed. Some preliminary results from moorings, and SAR data are summarized as follows:

On April 26, 2000, ADCP data on IW1 mooring with water depth of 400 m shows a huge mode-one depression wave which is corresponding to the soliton observed on SAR image in Figure 1. The mixed layer depth was estimated to be 130 m from the zero-crossing of current profile. Also, the mixed layer depth was approximately 100 m and 110 m from CTD castings on April 8th and 30th, respectively. The maximum current in the mixed layer was about 1.3 m/s in the west direction, and was more than 0.5 m/s in the east direction in the bottom. In general, the strongest soliton packets are generated during spring tide.

On April 13, 2000, ADCP data on IW2 mooring in shallow water (100 m depth) shows a mode-one elevation wave. The mixed layer depth was estimated to be 50 m. The maximum current in the mixed layer was about 0.75 m/s in the east direction, and was more than 0.25 m/s in the west direction in the bottom layer which is typically induced by mode-one elevation waves. In general, the elevation type internal waves are observed in shallow water where the mixed layer is thicker than the bottom layer.

The thermistor chain data from mooring IW3 on April 7, 2000 indicate the mode-two internal waves with negative temperature fluctuation in the mixed layer and positive value in the bottom layer. The mode-two waves were lagging behind the diurnal tide and mode-one waves by about 7-hours since mode-two waves have slower wave speed than mode-one waves. From the phase speed difference between mode-one and mode-two, the separation of these waves were started from approximately 14 km offshore. That means these mode-two waves were generated at shelf-break with water depth of 600 m to 1000 m.

The mesoscale variability, mean horizontal and vertical shears and varying stratification near the shelf-break are highly transient in April during the spring transition from winter monsoon to summer typhoon season. Therefore, the evolution of internal solitons in the ASIAEX test area at shelf-break will be quite complicate in April with many interested features such as mode-two solitons. The solitons will be in transient with continuous evolution and dissipation along the shelf. The impact on acoustic volume interaction will also be quite interesting and significant. The preliminary survey from ASIAEX 2000 definitely helps on the planning for the major field experiment in 2001. For the internal wave study, it is hoped that issues on generation, evolution, and dissipation in SCS can be addressed based on the data analysis of ASIAEX project.

## IMPACT/APPLICATIONS

It is clear that these internal wave observations in the South China Seas provide a unique resource for addressing a wide range of processes (Liu et al., 1996). These processes are listed as follows: the generation of elevation internal waves by upwelling, the evolution of nonlinear depression waves through the critical depth, the disintegration of solitons into internal wave packets, internal wave breaking induced by solitons, the generation of mode-two internal waves, and internal wave-wave interaction. The inclusion of these physical processes is essential to improve quantitative understanding of the coastal dynamics. The effects of internal wave on acoustic propagation is a very important issue as demonstrated in the Yellow Sea Acoustic Experiment carried out in August, 1996. The ASIAEX will be conducted in the East and South China Seas in year 2001. One of the major tasks is to study the effects of large-amplitude internal wave packets on the propagation and scattering of sound.

Due to the frequent fishing activities in the area, the thermistor chains on four surface moorings were lost three weeks after deployment during the survey test of ASIAEX in April 2000. The loss of four surface moorings in three weeks (not just instruments but also measurements) is a serious problem. The issues of how to protect mooring instruments have to be addressed for next year's major ASIAEX field test and any long-term mooring program. One of the solution for future consideration is to hire the guard fishing ships to protect moorings during the active fishing season.

## TRANSITIONS

The internal wave evolution model developed by Dr. Antony Liu has been used in a NRL study of internal wave effect on acoustic propagation. Recently, the internal wave distribution maps from more than three hundreds of ERS-1/2, RADARSAT and Space Shuttle SAR images in the East and South China Seas from 1993 to 1998 have been compiled for ASIAEX field test planning. These internal wave distribution maps are the most recent and important information for future planning of internal wave related field tests in these areas. Near real-time processed SAR images can be very helpful for scientists on research ship to coordinate the survey strategy. Dr. Liu has actively participated in the field test planning and coordinates the joint efforts between participants from the US and Taiwan. A validated and calibrated internal wave model can be very useful for understanding of shelf processes and for the applications of the internal wave effect on oil drilling platform, nutrient pump, sediment transport, and acoustic propagation.

## RELATED PROJECTS

This study is jointly funded by ONR Ocean Acoustics Program for ASIAEX support. Dr. Antony Liu has taken a sabbatical for six months (January to June 2000) at Taiwan and has established an internal wave project with the National Taiwan University as a part of ASIAEX program. Hydrographic surveys by Taiwan's research ships with CTD casts, thermistor chains, acoustic echo sounder, and moored ADCP will be conducted during ASIAEX 2001 by Prof. David Tang and Joe Wang of the Institute of Oceanography of the National Taiwan University and Prof. Ming-Kuang Hsu of the National Taiwan Ocean University. The ERS-2 and Radarsat SAR data will be collected and processed in near real-time at the Taiwan ground station. These in-situ measurements will provide a calibration on SAR observations and inputs for the numerical simulation of wave evolution on the continental shelf.

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